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The equipment procured under the FY2000 DURIP grant is a Scanning Laser Doppler Vibrometer system. The equipment has significantly enhanced the research capabilities and educational activities in the Active Materials and Structures Laboratory (AMSL) at MIT. This report summarizes the application of the Scanning Laser Doppler Vibrometer and its usefulness to the research and educational activities in AMSL.

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1. Introduction

The equipment procured under the FY2000 DURIP grant is a Scanning Laser Doppler Vibrometer system. The equipment has significantly enhanced the research capabilities and educational activities in the Active Materials and Structures Laboratory (AMSL) at MIT.

The Scanning Laser Doppler Vibrometer (shown in Figure 1) is an optical instrument that employs state-of-the-art laser technology and computer software driven data acquisition system to measure acceleration, velocity and displacement of points on a vibrating structure. The equipment is capable of providing faster, more complete, more accurate and more convenient means than traditional techniques to obtain dynamic response including 3D-mode shape data and animation of a variety of vibrating structures ranging in size from macro to micro levels.

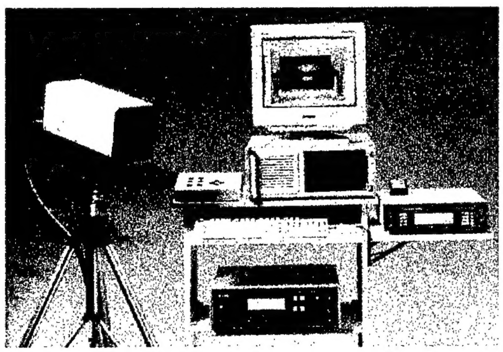


Figure 1: Scanning Laser Vibrometer

AMSL has employed the Scanning Vibrometer system in the identification of system dynamics in various ongoing research projects in the lab. Previously, dynamic characteristics of systems were obtained by means of conventional techniques such as mounting accelerometers on to the vibrating structure or using stationary optical probes. These techniques were not only tedious and error prone, but also limited in their functional range and capabilities. However, by means of a scanning laser vibrometer it has been possible to acquire significantly higher quality modal data on the various research conducted in the lab. The proposed scanning laser vibrometer enormously benefit the following projects:

- DARPA funded micro-hydraulic energy-harvester program.
- ONR funded micro-hydraulic actuator program.
- Boeing funded program in active control of helicopter blades.
- ONR funded program on control of acoustic radiated noise from thick-walled cylinder shells.
- ARO funded MURI program on active acoustic control.
- Development of solid-state ultrasonic motor.

Besides, the proposed equipment was also useful as an educational tool in the Undergraduate Research Opportunities Program (UROP) and one undergraduate thesis.

This report summarizes the applications of the Scanning Laser Doppler Vibrometer and its usefulness to the research and educational activities in AMSL.

2. Significance of the Scanning Laser Vibrometer

The research conducted in the Active Materials and Structures Laboratory (AMSL) at MIT involves a variety of actively controlled structures and systems ranging in size from large aircraft wings to tiny micro actuators (MEMS). A substantial amount of effort in these research activities is devoted to control and measurement of complex dynamic characteristics of these structures. A very clean, high quality data is extremely critical to the research conducted in the lab. Prior to obtaining the Scanning Vibrometer system, modal analysis of these structures was performed by traditional techniques such as wiring the structures with arrays of accelerometers and strain gages in case of large structures, and more sophisticated electronic speckle pattern interferometer (ESPI) and fiber optic probes in case of tiny structures of the order of a few millimeters. The required data acquisition by these techniques had several limitations besides being a very tedious and time-consuming effort. These limitations had direct impact on the quality and also, the scope of the research conducted in the lab. Some of these limitations are identified as follows:

The Scanning Laser Vibrometer not only eliminated all the above limitations but also enabled the visualization of complex dynamic behavior of systems that is impossible to accomplish by any other means. Unlike conventional transducers, scanning laser vibrometery is completely non-contact and measurements are made at points where the laser beam strikes the structure. The vibrometer system features an interactive video system that produces a live, full-field image of the test object. This live image is used to define scan geometry on the test surface by positioning a variable density grid in background of the acquired image, and also to remotely position and adjust the scan head and laser for data acquisition. The laser then scans over the selected area and vibration spectra are computed at every point by a fast high power dual-channel FFT analyzer and a sophisticated algorithm. The outputs include power spectrum as well as color coded vibration maps at each selected vibration frequency overlaid on the video image. By clicking on a location of interest, the user can view the individual data at any point on the structure, including FRF, H_1, H_2, coherence, cross-power spectrum, real and imaginary parts. Also, operating deflections can be displayed and animated in 3D or 2D instantly. Data can be also transferred to external platforms for further processing.

The Scanning Laser Vibrometer equipment which has an estimated useful life of at least 10 years provided several advantages over traditional techniques both in terms of accuracy of results obtained as well as cost and time savings. Some of the highlights of the advantages are as follows:

- As the laser beam of the scanning vibrometer can be variably focused down to a couple of µm in a small area or over a large distance, the vibrometer system enables accurate measurements on very tiny structures such as micro-electromechanical system (MEMS) as well as large structures such as aircraft wings and fuselage.
- Due to non-contact nature, the measurements obtained using the vibrometer are not affected by properties of test surface and environmental conditions such as temperature and pressure.
- The vibrometer system adds no mass or stiffness to structure, and thus capable of providing more accurate modal data.
- The vibrometer system is capable of providing quicker and more detailed results with very fine spatial resolution that is not feasible with accelerometers.

- The vibrometer system is capable of measuring the vibrations of large curved surfaces such as a fuselage or a torpedo more accurately and more conveniently than conventional techniques.
- The vibrometer system provides higher output linearity and inherent higher accuracy, and it has virtually no upper limit frequency.
- The vibrometer system eliminates the need for large transducer arrays for full-field measurements, and the high measurement densities avoid spatial aliasing problems during area measurements.
- The ability of the vibrometer system to produce 3D animation of the entire test object at any frequency from the vibration spectra allows for a clear visualization of the phenomenon and enables quick detection of any undesirable behavior. This is not feasible using any of the traditional techniques.
- As the vibrometer system involves no transducers to attach, connect, calibrate, phase and detach, it improved the efficiency of data acquisition process.

The details of the usefulness of the Vibrometer system in various ongoing research programs as well as educational activities in AMSL are summarized in the following sections.

3. Summary of Results

3.1 Use of the Scanning Laser Vibrometer in Research

3.1.1 Micro-Hydraulic Transducers Research

Principal Investigator: Nesbitt Hagood
Sponsor: DARPA and ONR
Contract Number: DAAG55-98-1-0361 and N00014-97-1-0880
Award Amount: $3,586,891 and $840,294

Thrust of the research

The micro-hydraulic transducers (MHT) research in AMSL is focused on the development of meso- and micro-scale actuator and energy harvesting systems with unprecedented power densities. This transducer technology integrates various enabling technologies and ideas which include: solid-state transducer materials, MEMS microfabrication techniques, and hydraulic power rectification. The MHTs consists of a piezoelectric drive element, two actively-controlled valves, a low pressure fluid reservoir, and a high pressure fluid reservoir. The piezoelectric drive element, composed of a piezoelectric cylinder bonded to a moveable silicon plate, is contained within a fluid pumping chamber. The two active valves regulate flow into and out of this chamber. In response to an AC voltage signal, the drive element expands and contracts, thereby pumping fluid from one potential level to another.

One of the primary components in the actuator system is the drive element or a micro actuator (see Figure 2). Fabrication of the drive element requires reliable bonds between the silicon, pyrex, and piezoelectric components, as well as accurate alignment of the piezoelectric cylinder in the center of the drive element chamber. The controllability of the top membrane etching procedure is crucial to attain desired membrane characteristics, such as the membrane thickness, the membrane width, and the etched fillet radius. Small variations in these parameters can result is large performance variations of the drive element.

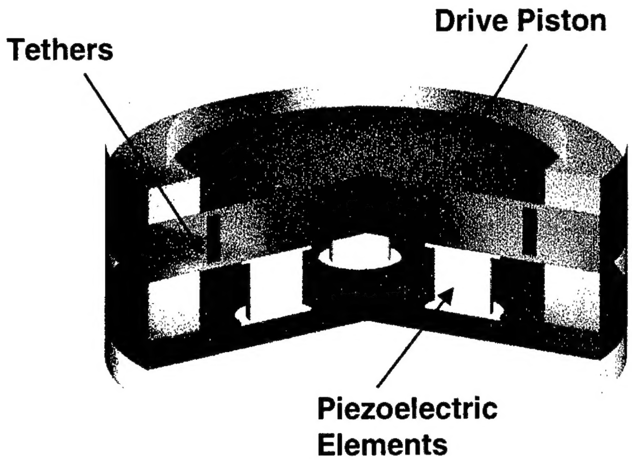


Figure 2: MHT micro-actuator/drive element.

A series of drive elements (10×10×8 mm^3) was successfully fabricated and each drive element was characterized for its dynamic behavior. Results of these tests will indicated how accurately and consistently the drive element characteristics have been met.

Impact of the Scanning Laser Vibrometer on the research

The new scanning laser vibrometer system is far superior to the MTI probe system that was previously used for evaluating the effects of fabrication procedures on the performance of these drive element components. The Vibrometer system offers the capability to resolve the membranes into a very fine grid and evaluate the behavior of each individual grid point throughout a specified frequency range. In this way, the measured mode shapes have extremely fine resolution and no manual movement of the equipment is required for measuring different locations on the membrane.

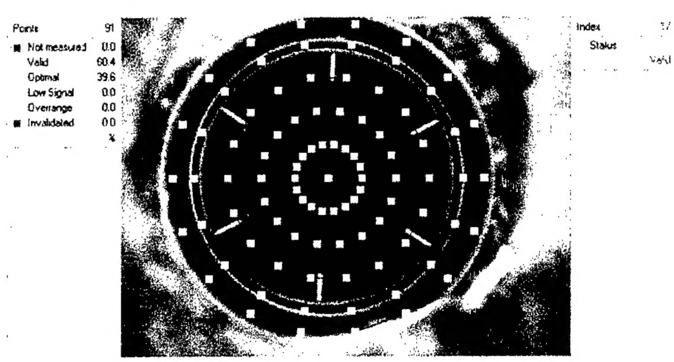


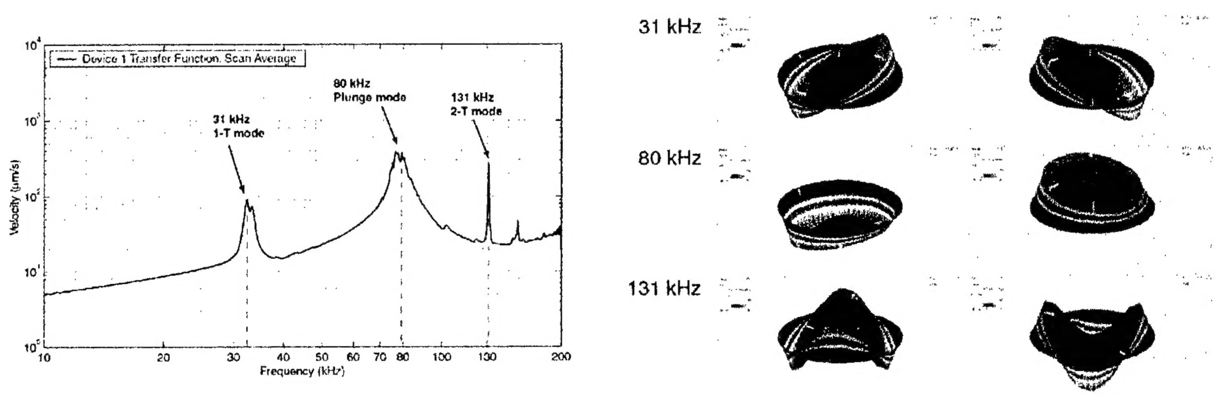
Figure 3: Grid points on the drive element for measurement of mode shapes.

MHT also involves tiny valves of diameters about 0.2 mm and pressure sensors of even smaller diameters. The MTI system is not capable of obtaining even a single measurement on these tiny valves. The scanning vibrometer system, however, will enable measurements down to the required scale.

Figure 4(A) below shows the transfer function of averaged velocity over the scanned surface versus frequency, and Fig. 4(B) shows the 3D mode shapes of the actuator obtained using the scanning laser vibrometer. The device experiences a 1-Θ tilt mode at 31kHz, followed by a plunge/umbrella mode at 80kHz, and a 2-Θ mode at 131kHz.

A slight frequency difference in the 1-Θ mode between finite-element model and experiment was observed, which is likely due to imperfect placement of the cylinder beneath the piston or non-uniform fillet radii around the piston etched trench. Also, a slight tilting of the piston surface in the umbrella/plunge mode is observed, and is again likely influenced by imperfect piezoelectric cylinder placement or fillet radius etching.

Obtaining such results and insight into the defects in the microstructres would have been almost impossible with optical probe approach. In conclusion, the scanning laser vibrometer proved to be an invaluable tool in the analysis of microstructures.



(A) (B)

Figure 4: Experimental modal analysis of the actuator: frequency spectrum (left) and mode shapes (right) obtained from the scanning vibrometer measurements.

3.1.2 Ultrasonic Motors Research

Principle Investigator: Nesbitt W. Hagood
Prospective sponsor: DARPA

Thrust of the research

The focus of the ultrasonic motor research in the lab is directed toward a better understanding of the fundamentals of a piezoelectric rotary ultrasonic motor of the traveling-wave type, including the development of a novel two-sided design for improved torque output. Traveling-wave motors have just begun to enter into commercial applications, but through improved modeling techniques and validating experimental observations, understanding those key factors which determine a motor's performance will help in finding increasingly more applications for these powerful actuators.

Ultrasonic motors (Figure 5) utilize the high specific-energy output of active materials at high frequencies to provide large power output at useful, low frequencies. They can be classified as rectifying actuators in which small reciprocating displacements generated by active materials are rectified by frictional contact mechanisms into large continuous stroke. Ultrasonic motors have the several advantages over electromagnetic motors which includes high torque density, self-braking, silent operation, negligible backlash, quick response, potential for direct drive, flexibility of shapes, scope of miniaturization.

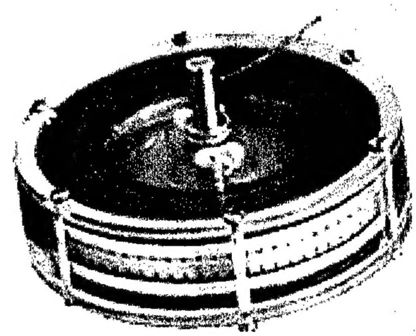


Figure 5: The ultrasonic motor.

Impact of the Scanning Laser Vibrometer on the research

At the heart of all ultrasonic motors is a structural component, often called the stator, bonded with active materials that are used to excite a prescribed resonant mode. The quality of this resonant mode is vitally important to the motor's performance, so care must be taken in both design and manufacturing to assure text-book behavior of the desired vibration mode. In the traveling-wave motor, two orthogonally excited degenerate modes of an annular disk are superposed to generate the propagating wave. Many factors such as modal coupling or mode locking due to unintentional structural asymmetry can detract from the ability to generate such an ideal traveling wave, thus greatly degrading performance. It is, therefore, important to visually inspect the modal characteristics of the prototype stator to assess the quality of the otherwise invisible wave.

Certainly, the most ideal measurement tools in ultrasonic motor research are those featuring non-contact displacement sensing, whether for monitoring vibration amplitude during operation or for characterization of the modes of the stator. Previously, the research has relied on measurement systems such as an electronic speckle pattern interferometer (ESPI) and a fiber optic displacement sensor, but all have had their limitations. The fiber optic probe, for instance, takes only a single point measurement, and the ESPI system, although capable of providing full-field displacement sensing, does not provide vital phase information. The scanning laser vibrometer overcomes these shortcomings by providing vibration information in the form of both amplitude and relative phase over the full field of interest. Also, as the vibrometer directly measures velocity instead of displacement, it results in tremendously better displacement resolution at the high frequency range that ultrasonic actuators operate.

Vibration measurements taken of the prototype motor stator demonstrate how effective the system is in observing subtle problematic issues with respect to the quality of the excited waves. For example, as shown in Figure 6, the standing wave mode of the prototype stator does not correctly align with the piezoelectric electrode array. One can see clearly that the zero displacement contours do not correctly coincide with the etch lines; the mode is slightly rotated from its desired orientation. Normally, this observation would be considered of minor significance, but with regard to the performance of an ultrasonic motor, it has a dramatic effect on the ability to generate a constant amplitude traveling wave. Use of a scanning laser vibrometer makes quantifying this subtlety very efficient and accurate.

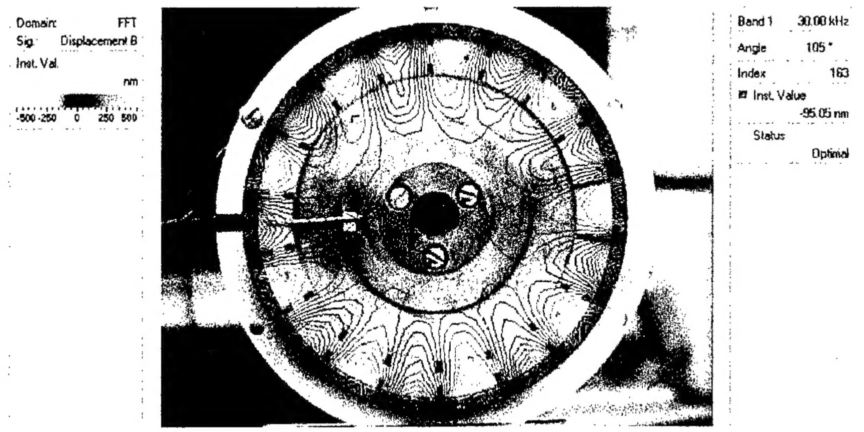


Figure 6: Displacement data of a standing wave superposed on the video feed illustrates the undesirable "rotation" of the mode with respect to the electrode pattern.

Figure 7 shows a single frame of a 3D animation of the traveling wave displacement measurement at a frequency slightly above resonance. The superposition of two ideally formed standing waves would result in a constant amplitude traveling wave, but as this data proved, seemingly minor deviations from perfection such as that depicted in Figure 7 result in drastically degraded traveling wave excitation and, consequently, poor operation and performance of the motor system.

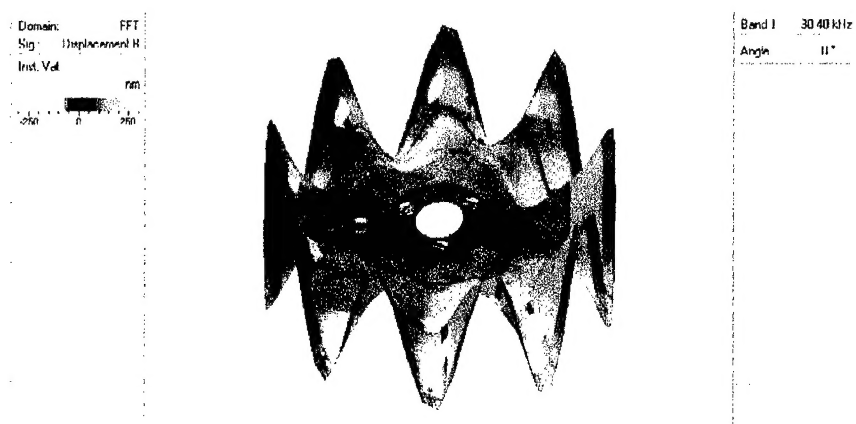


Figure 7: 3D mesh view of a traveling wave. When animated, the effect of imperfect excitation of the standing waves becomes evident in the "beating" of the traveling wave amplitude.

The ultrasonic motor research in AMSL has been greatly advanced by the use of the scanning laser vibrometer system. Experimental observation of phenomena that could otherwise only be speculated and modeled was made possible by the extraordinary capabilities of the system. Before observation with the scanning laser vibrometer, certain problematic issues with the research were overlooked because of the difficulty of quantifying them with present measurement devices, but with the Vibrometer system, a much greater understanding of the real problem at hand has been achieved.

3.1.3 Active Rotor Blade Research

Principal Investigators: Steven R. Hall and Nesbitt hagood
Sponsor: Boeing
Contract Number: MDA972-98-3-0001
Award Amount: $765,489

Thrust of the research

The objective of the rotor blade research at MIT is to develop blade-mounted actuators for use in helicopter rotor vibration reduction control systems. Two different approaches have been pursued at MIT for this task. The first uses active material, bonded directly to the rotor blade to twist the entire structure. The second utilizes a discrete actuator located in the rotor blade spar that controls a trailing edge servo-flap through a push-rod. Flap deflections cause aeroelastic forcing of the rotor to affect the global rotor aerodynamics. The research for both approaches is focused on developing both the actuators and reliable rotor blade manufacturing techniques and in identifying the performance of the active blades in Mach scaled hover tests.

Impact of the Scanning Laser Vibrometer

The scanning laser vibrometer was used to identify the modes on the active rotor blade incorporating a discrete actuator powering a trailing edge servo-flap. The modes were identified while the blade was attached to the hover test stand at MIT. The laser module was mounted on the floor and the laser was focused on the bottom surface of the blade while sending in a 10-300 Hz sine sweep "chirp" signal into the servo-flap actuator. Using the scanning laser vibrometer, animation movies were generated clearly showing the shape of the rotor-blade modes and the interaction of the servo-flap with these modes. Figures 8 and 9 show still frames from the animations of the first elastic torsion mode and the fundamental actuator mode, respectively. Note that the vibrometer was able to capture both the large servo-flap deflections and the smaller resulting blade motion, simultaneously.

The results from these tests have impacted a number of areas of the discrete actuator rotor blade project. First, the data clearly identifies the fundamental mode of the actuation system itself, as shown in Figure 10. Because of hinge friction in the actuation system, it was difficult to clearly identify this mode in the past. Secondly, and more importantly, the laser vibrometry data enables clear visualization of the distribution of dynamic modes of the rotor blade. The location of these modes can give a great deal of information on the impact of advanced blade manufacturing techniques on the rotor blade structure. In addition, the harmonic location of these modes has a profound impact on the effectiveness of the actuation schemes in controlling hub vertical shear. In the absence of the laser vibrometry system, strain gages, distributed around the rotor blade were used to aid in identifying the blade modes. While strain gage bridges can be wired to pick up strain in a preferential direction, they will tend to pick up strains from all blade modes to some extent. Because of this, it is sometimes difficult to unequivocally identify blade modes from strain gage data alone. In fact, it usually requires one to study the strain gage data as a function of rotor speed and compare the data with predicted models to develop confidence in the identification of a mode. Because the scanning laser vibrometer identifies the entire mode shape of a structure at once, it makes the modal identification a trivial process and saves a great deal of time and cost.

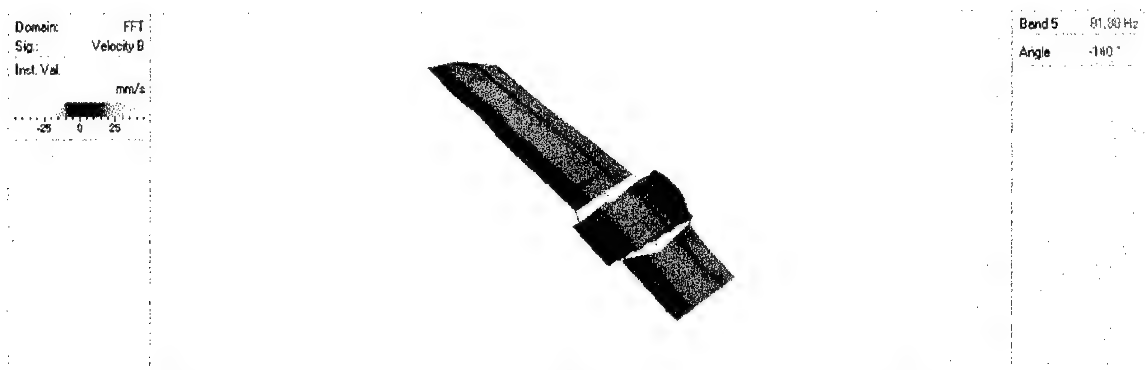


Figure 8: First Elastic Torsion Mode of Active Flap Rotor Blade.

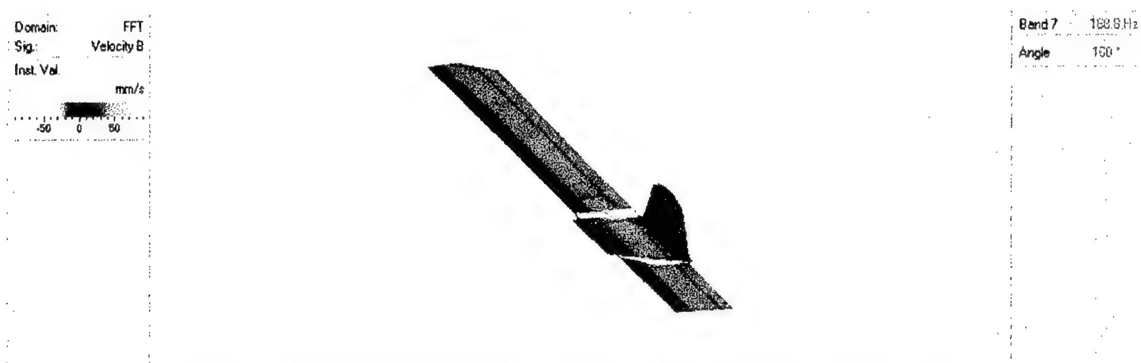


Figure 9: Fundamental Actuator Mode of Actuation System.

Although not highlighted in Figures 8 and 9, the laser vibrometry data was also able to identify a small delamination in the composite rotor blade near the root. The use of the vibrometry system to identify damage in similar composite structures would aid in evaluating their structural health. In addition, quickly identifying the location of local damage can speed the structural redesign process.

3.1.4 Active Structural-Acoustic Control

Principle Investigator: Nesbitt W. Hagood
Sponsor: ARO
Contract Number: DAAH4-95-1-0104
Award Amount: $4,997,209

Thrust of the research

The Active Structural-Acoustic Control Project, an ARO funded MURI program, seeks to minimize the noise in interior cabins of helicopters by reducing the vibrations of the fuselage. Piezoceramic actuators and piezopolymer sensors are used in a robust control loop to minimize the fuselage vibrations. The location of the actuators and sensors dictates which modes of vibration can be controlled.

Impact of the Scanning Laser Vibrometer on the research

Knowledge of the accurate structural dynamics and mode shapes of the fuselage structure is extremely important for the optimal locations of transducers and knowledge of open-loop and closed-loop dynamics is critical to optimize noise reduction. Standard modal identification techniques do not present an accurate representation of the system and cannot be used to compare open-loop and closed-loop dynamics. Currently, there are no effective techniques to image the mode shapes on the fuselage. We have attempted to use arrays of accelerometers to measure the modes shapes. The accelerometer-based modal identification not only takes weeks to perform and analyze but also the weight of the accelerometers shifted the sensitive mode shapes. With the scanning laser vibrometer, we measured some of the dynamics of the helicopter fuselage test-bed using the vibrometer. The non-contacting and unobtrusive measurements obtained using the scanning laser vibrometer were not only quick, but also facilitated a far better understanding of the complex dynamics. Such an understanding allowed us to achieve better noise control by quickly imaging the vibration modes and optimizing the transducer locations.

Figure 10 illustrates the deflection shape at 1178 Hz from the excitation of the control actuators and Figure 11 illustrates the closed-loop deflections of one panel of the helicopter fuselage. The grid lines indicate each point at which the structural dynamics were measured. Red color in the figure corresponds to large amplitude motion and green color corresponds to small motion. The coupling between different panels on the helicopter holds strong implications on the style of control that can be performed.

A scanning laser vibrometer was also important for understanding why a control strategy is not working. For example, we had designed one controller that minimized the structural deflections measured by accelerometers but did not minimize the acoustic noise. The dynamic measurements from the scanning laser vibrometer revealed that the controller minimized the dynamics at the location of the sensors, but increased the motion elsewhere. This type of insight is only obtainable with a scanning laser vibrometer.

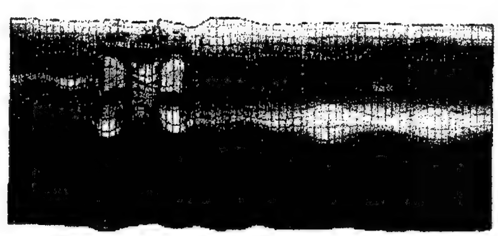


Figure 10: Scanning laser vibrometer image of the deflection of the helicopter fuselage.

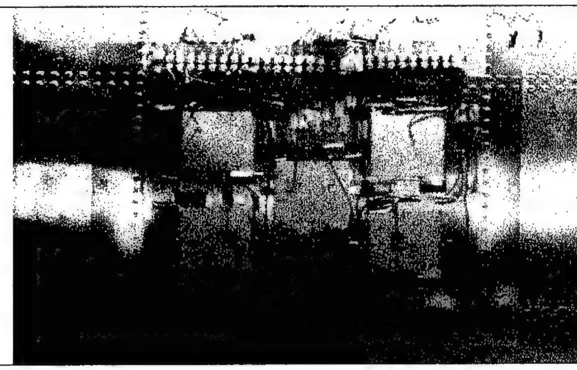


Figure 11: Closed-loop deflections of one panel of the helicopter fuselage.

3.1.5 Active Control Of Radiated Noise (ACORN) Project

Principal investigator: Prof. Steven Hall
Sponsor: Northrop Grumman Corporation
Contract number: 87JJ-OJ-9148
Award Amount: $428,944

Thrust of the research

ACORN (Active Control Of Radiated Noise) program seeks to reduce noise from torpedo shell vibration through a systematic method of constructing a conformal actuator coating around a torpedo. Since a torpedo structure is too stiff and rigid, it is impractical to control directly the torpedo vibration. The panels used as a conformal coating, called "smart panels," contains several accelerometers on the top and bottom side of the panel, and can be used as a 1-3 composite actuator. Figure 12 shows a picture of the experimental setup of this project.

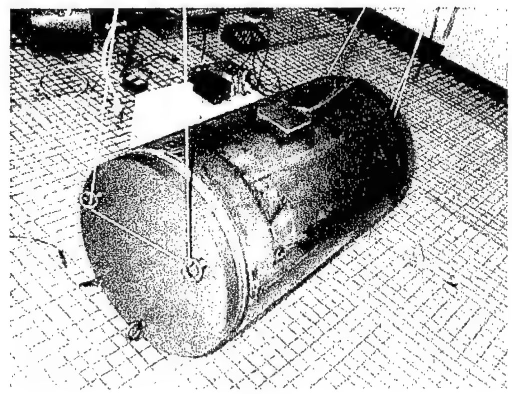


Figure 12: Experimental setup for active control of radiated noise from torpedo shell.

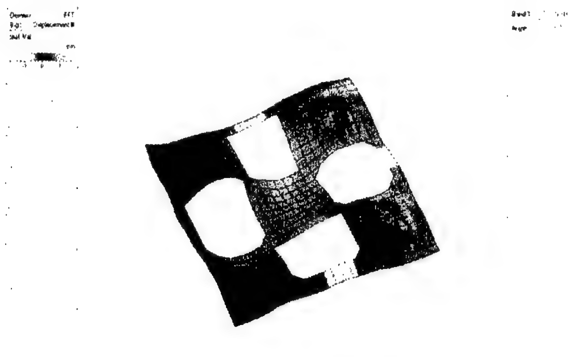
The control loops are divided into two parts: local control and global control. For local control, each panel is used as a sensor-actuator pair, which is almost collocated. Feedback control, which takes outer acceleration and applies proportional gain to panel actuator to servo panel position to zero, and feed-forward control, which takes acceleration on the inside surface of the panel and commands equal and opposite panel displacement, are implemented at the same time. For global control, fifty-five panels are attached on the torpedo and while each panel is used as a sensor-actuator pair and closed independently using local control, the whole panels constitute the global control, which performs a high-level job of coordinating the activities of local controller with an intention of achieving a global picture of performance.

Impact of the Scanning Laser Vibrometer

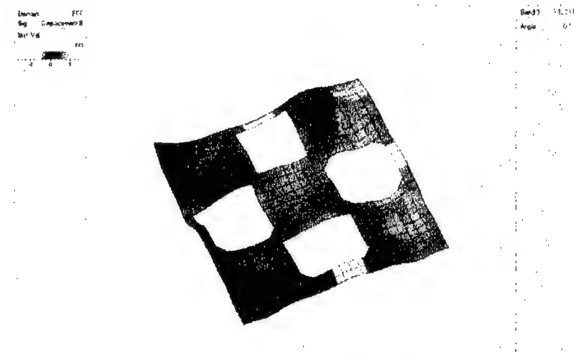
In order to design an efficient controller, for both local and global control, acquiring clean dynamic characteristics of the system is critical. For local control, the vibration characteristics of the panel actuator, which may be easily neglected, is found to be critical in the closed-loop stability and performance. For global control, a dynamic coupling between fifty-five panel actuators, as well as a global mode shape of the torpedo structure, should be clearly determined for an efficient MIMO controller. Using the scanning laser vibrometer system, it was possible to obtain mode shape of the panel and the torpedo more accurately and more conveniently than by means of accelerometers. Figure 13 shows some of the mode shapes of the panel actuator and the torpedo obtained using the scanning laser vibrometer system.

The dynamic characteristic of the panel actuator, which is obtained using the scanning laser vibrometer, explained the reason for the difficulties we have had in the design of local controller, and helps resolve these problems. Furthermore, it enabled us to obtain the mode shape of huge and complex structural systems with extremely fine resolution without manual movement of the equipment, which is impossible for the conventional method using accelerometers. Therefore,

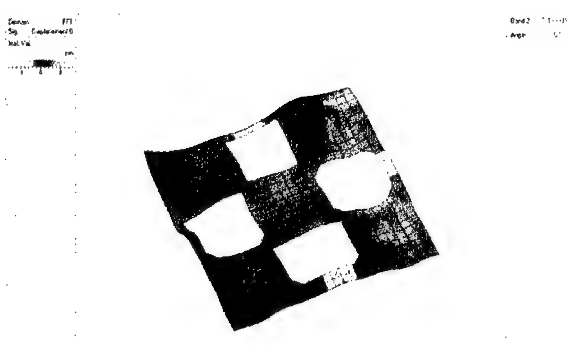
the scanning laser vibrometer system enabled the design of efficient controller for the reduction of noise from structural vibration of torpedo.



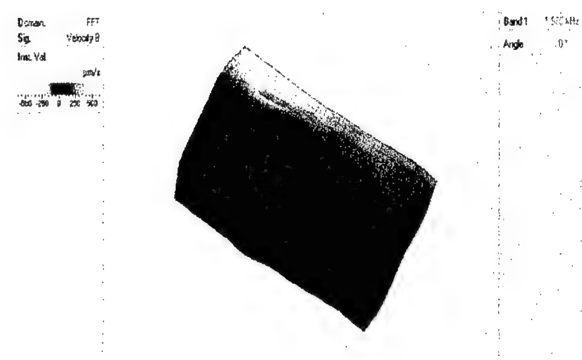
Panel mode at 3019 Hz



Panel mode at 3163 Hz



Torpedo mode at 985 Hz



Torpedo mode at 1965 Hz

Figure 13: Mode shape of torpedo and pannels obtained by scanning laser vibrometer.

3.1.6 Shape Estimation of a Vibrating Structure

Principle Investigator: Nesbitt W. Hagood
Sponsor: ARO
Contract Number: DAAH4-95-1-0104
Award Amount: $4,997,209

Thrust of the research

The thrust of this research is to develop a method that is capable of estimating the dynamic shapes of structures. Current methods rely on applying the static methods at each time step. Such methods suffer from a great degree of aliasing since the higher modes, which contribute little deflection, have high strains. The basic idea behind this new methodology is to add a temporal filter and treat the higher modes as noise. The temporal filter works best with knowledge of the modes of the structures, i.e. using a finite element code.

Impact of the Scanning Laser Vibrometer

The laser vibrometer was ideal to this project since the true deflection mode shapes could provide measurements at all the points in a non-contact manner. Such measurements allowed for a better model of the structure, which in turn allowed for better estimation of the behavior of the structure. Additionally, the vibrometer allowed a better method for identifying the accuracy of the method. Previously, the measurements were obtained by means of a single stationary laser at the tip of a cantilevered beam. For more complicated structures, even a simply supported plate, the choice of error metric was complicated. However, the scanning vibrometer was able to check multiple points for a better indication of whether the method is successful. Figure 14 shows the mode shape featuring bending and torsion at 556 Hz obtained by means of a laser scanning vibrometer.

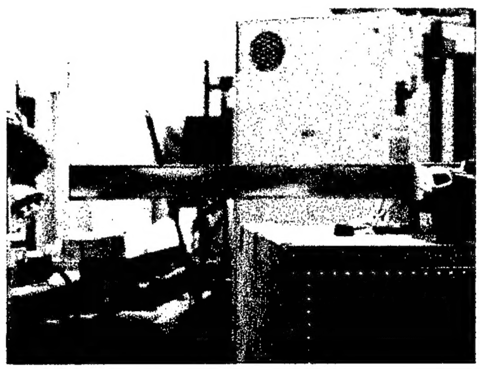


Figure 14: Vibration mode shape of the cantilevered beam that was used in shape estimation.

3.1.7 Structural Health Monitoring In Composite Materials

Thrust of the research

Cost-effective and reliable damage detection is critical for the utilization of composite materials in structural applications. Non-destructive evaluation techniques (e.g. ultrasound, radiography, infra-red imaging) are available for use during standard repair and maintenance cycles, however by comparison to the techniques used for metals these are relatively expensive and time consuming. This research investigates an alternative experimental approach using structural frequency response for Structural Health Monitoring in composite materials. The experimental results are obtained by modal analysis techniques applied to rectangular laminated graphite/epoxy specimens containing representative damage modes, including delamination, transverse ply cracks and through-holes. Changes in natural frequencies and modes are then found using a scanning laser vibrometer, and 2-D finite element models were created for comparison with the experimental results. The models accurately predict the response of the specimens at low frequencies, and the method appears to be appropriate for detecting global changes in stiffness, and hence damage, for relatively large structures at a low power and weight cost, but the local excitation and coalescence of higher frequency modes makes mode-dependant damage detection difficult and most likely impractical for structural applications. The final goal of this research is to provide useful guidelines in sensor selection and system architecture for designing a reliable SHM system for composite structures.

Impact of the Scanning Laser Vibrometer

There were three sets of outputs for each test on the vibrometer. The velocity magnitude response to the frequency range inputted into the piezos was recorded by the vibrometer system. The vibrometer software was used to compute the normal mode maximum peaks and corresponding deformation shapes. A few selected mode shapes from the vibrometer display are presented in Figure 15 to be later contrasted to the predicted shapes, and Figure 16 displays the velocity magnitude response to a frequency range below 500 Hz for all of the tested specimens. From this plot, the conclusions regarding the true effect of various damage on the frequency response of a system can be extracted.

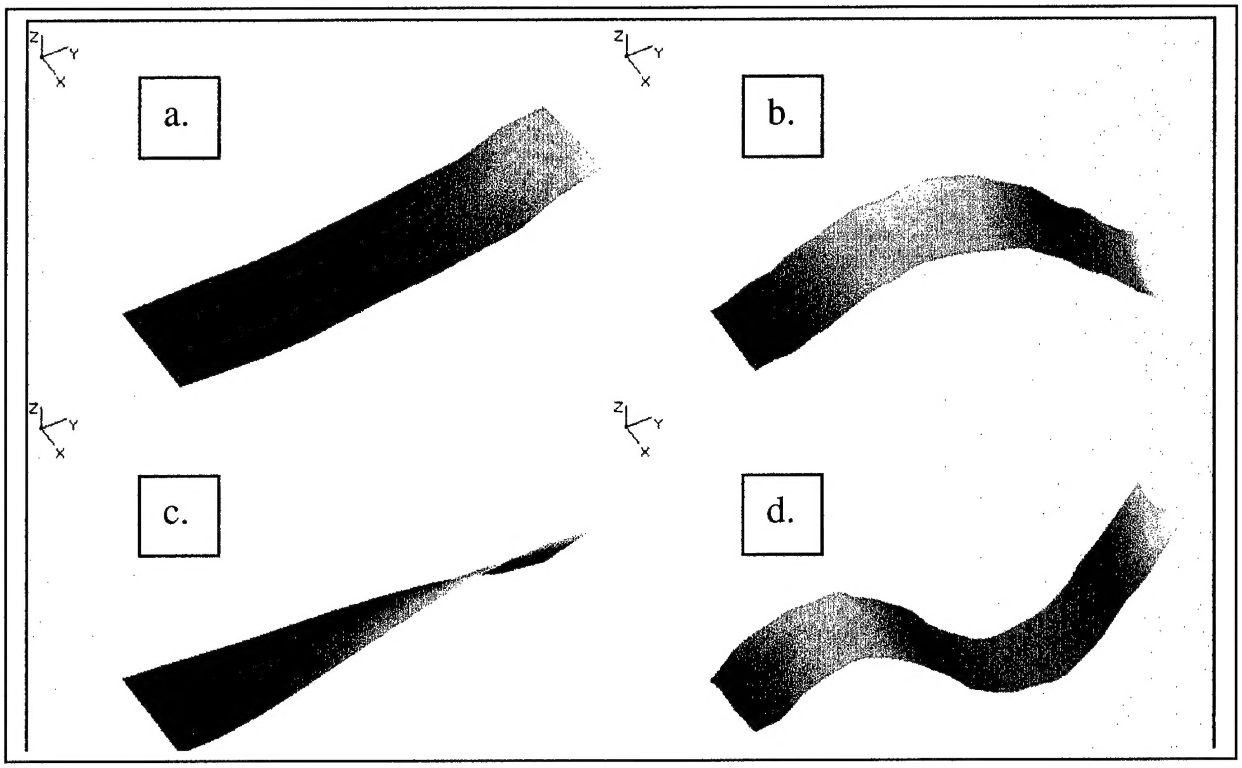


Figure 15: First four mode shapes of control specimen plotted using laser vibrometer data. a. first bending, b. second bending, c. first torsion, d. third bending

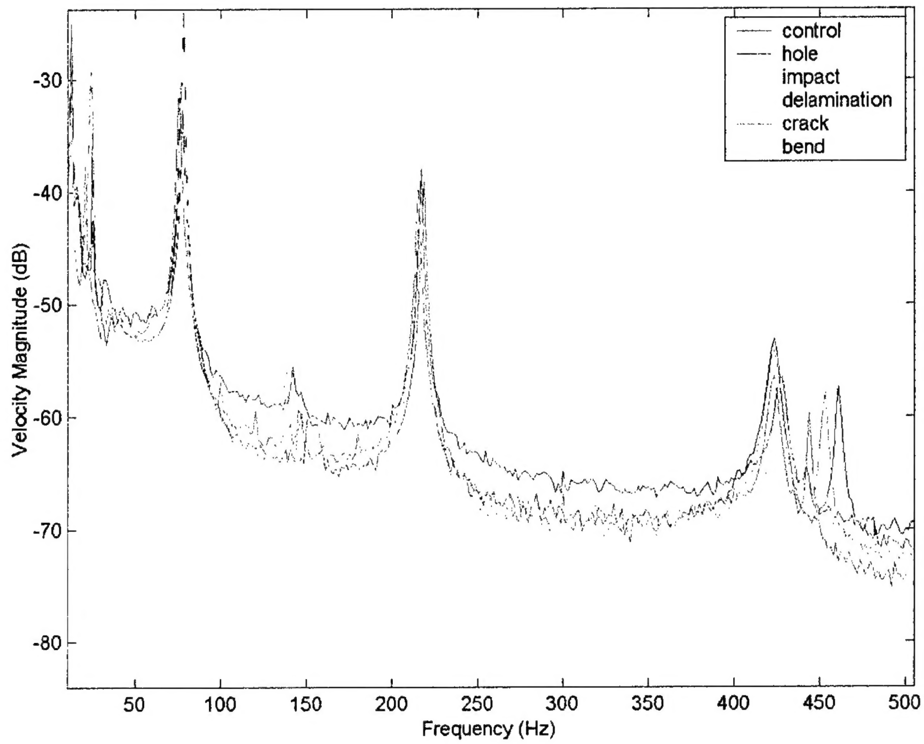


Figure 16: Frequency response plot from vibrometer for all specimens, range of 0-500 Hz

3.2 Results : Use of the Scanning Laser Vibrometer in Education

The Scanning Laser Doppler Vibrometer equipment was used in training of undergraduate students in the measurement dynamics of micro-structures. The students who benefited most from the equipment are:

Rick Chang: "*Dynamic Precision Measurements Of Microhydraulic Transducer Components Using A Laser Scanning Vibrometer*," B.S. Thesis, Spring 2001.

Blair Connoley: "*3D Modal Analysis of Micro-structures*," Undergraduate Research Opportunity Program, Summer 2001.

4. Personnel

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